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The future of lithium availability for electric vehicle batteries

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ABSTRACT

Electric vehicles using lithium batteries could significantly reduce the emissions associated with road vehicle transport. However, the future availability of lithium is uncertain, and the feasibility of manufacturing lithium batteries at sufficient scale has been questioned. The levels of lithium demand growth implied by electric vehicle deployment scenarios is significant, particularly where scenarios are consistent with global GHG reduction targets. This paper examines the question of future lithium availability for the manufacturing of lithium batteries for electric vehicles.

In this paper we first examine some of the existing literature in this area, highlighting the levels of future lithium demand previously considered and pointing to the variables that give rise to the range of outcomes in these assessments. We then investigate the ways in which lithium availability is calculated in the literature based on both lithium demand from electric vehicles and lithium supply from both brines and ore.

This paper particularly focuses on the key variables needed to make an assessment of future lithium availability. On the demand side, these variables include future market size of electric vehicles, their average battery capacity and the material intensity of the batteries. The key supply variables include global reserve and resource estimates, forecast production and recyclability.

We found that the literature informing assumptions regarding the key variables is characterised by significant uncertainty. This uncertainty gives rise to a wide range of estimates for the future demand for lithium based on scenarios consistent with as 50% reduction in global emissions by 2050 at between 184,000 and 989,000 t of lithium per year in 2050. However, lithium production is forecast to grow to between 75,000 and 110,000 t per year by 2020. Under this rate of production growth, it is plausible that lithium supply will meet increasing lithium demand over the coming decades to 2050.

Contents

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1. Introduction

Electric vehicles (EVs) have the potential to significantly reduce the Well-to-Wheel emissions of road vehicles through the use of low carbon electricity and efficient lithium[3] batteries. However, the increasing debate on the availability of critical metals such as lithium raises questions regarding the feasibility of manufacturing lithium batteries at scale [1–3]. Large quantities of lithium will be needed to manufacture enough automotive batteries to meet 2050 decarbonisation scenarios [4–6] and some doubt has been cast over the mining sector's ability to satisfy this demand [7,8].

In this paper we use the term EVs to indicate all road vehicle types that have an electric drivetrain, including hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV),[4] battery electric vehicles (BEV) and fuel cell vehicles (FCV). This classification is broad and does not fully represent the variety of powertrain architectures. It is however practical for two reasons: (1) the literature often classifies vehicle technology in a similar way; and (2) these vehicle types all potentially use lithium batteries. It is important to differentiate among these vehicle types, however, since they have different battery requirements and are therefore likely to use different quantities of lithium.

This paper investigates the availability of lithium for the manufacture of batteries for the growing EV market. First, we examine the existing literature, focusing on the relationship between metal availability and EV manufacture, highlighting the types of variables and assumptions used in estimating future demand and availability. We then describe the difficulties in calculating future lithium demand in EV battery manufacturing. Section 4 discusses the issues surrounding future supply of lithium before comparing supply and demand issues in Section 5 and presenting conclusions in Section 6.

2. Existing assessments of EV lithium availability

A number of authors have explored the relationship between lithium availability and EV demand, ranging from pessimistic studies that suggest future EV demand cannot be met by lithium supply [7,8], to optimistic studies that find no significant constraint to ambitious EV market development projections [9]. Within these studies are a range of different assumptions which lead to the wide range of findings (Table 2.1).

While many of these studies predict no lithium supply constraints, few agree on the level of future EV manufacturing or the quantity of lithium needed to deliver those vehicles.

The assumptions leading to this range of outcomes include:

- the time horizon assumed;
- the number of vehicles manufactured at a given point in the future;
- the assumed size of batteries in different EV types;
- the share of the future EV market taken by different EV types; and
- the quantity of lithium per unit of battery capacity.

These issues are discussed in Section 3.

In addition to variables influencing estimates of future demand, there are a number of variables influencing estimates of future supply, which in turn influence estimates of the potential for and extent of any future lithium availability constraint for EVs. These include:

- estimates of lithium reserves;
- estimates of future lithium production rates; and
- estimates of future recycling rates.

These variables are discussed in detail in Section 4 in order to understand their influence on availability estimates, and sensible ranges for their assumptions.

3. Calculating lithium demand from EVs

The calculation of future lithium demand from EVs involves several factors and is subject to significant uncertainty. However, the common elements typically considered are:

- the number of EVs manufactured in the future;
- the size of EV batteries in kW h; and
- the lithium intensity per kW h of battery.

First we examine the plausible ranges of future EV deployment in Section 3.1, before examining the issues of material intensity per vehicle in Section 3.2.

3.1. The future size of the EV market

There are several scenario studies presenting a range of different outlooks of the future EV market. To illustrate the range of scenarios found in the literature Speirs et al. [10] compare several studies [6,11–14] disaggregated by vehicle type and over a range of time horizons, the earliest beginning in 2008 and the longest projecting to 2050. For example, in scenarios to 2050 global PHEV sales estimates range from 10 to 79 million vehicles per year, and BEV sales estimates range from 12 to 84 million vehicles per year in 2050. However, of those studies, the International Energy Agency (IEA) scenarios [6] are of specific interest as they:

- provide estimates of vehicle sales in 2050, a key year in terms of climate goals; and
- are based on an internally consistent scenario to halve global CO_2 emissions by 2050 compared with 2005 levels.[5]

[3] We use the term lithium battery to refer to any lithium-based battery chemistry, including current lithium-ion chemistries. In future it is possible that chemistries that use lithium metal, such as lithium sulphur and lithium air, will be adopted; hence the use of the generic term lithium battery.

[4] For consistency with key studies cited here we use the term 'PHEV' to indicate both parallel and series plug-in hybrid powertrain architectures. The latter are usually characterised by larger batteries and are also referred to as Range Extended Electric Vehicles (RE-EVs).

[5] According to the Intergovernmental Panel on Climate Change [15] this is the minimum necessary to maintain global average temperature rises to within 2 °C to 3 °C.

Table 2.1
Comparison of several studies that examine the potential material constraints to lithium battery manufacture.

Author	Forecast lithium supply constraint on EV manufacture	EV manufactured (millions per year)	By year	Lithium intensity per vehicle (kg)
Evans [10] Evans [11]	No	5 EV	2015	HEV: 0.23 PHEV: 1.35 BEV: 2.81
Gaines and Nelson [12]	No	~35 BEV & ~65 PHEV	2050	HEV: 0.17–0.64 PHEV: 0.93–5.07 BEV: 3.38–12.68
Gruberet al. [13]	No	> 600 EV	2100	HEV: 0.05 PHEV: 1.14 BEV: 3.85
Kushnir and Sandén [14]	No	4500 EV (cumulative)	2100	PHEV: 1.44 BEV: 5.76
Neubauer [15]	No	47 BEV and 60 PHEV	2050	PHEV: 0.6–1.9 BEV: 3.3–7.5
Tahil [7] Tahil [8]	Yes	4–8 PHEV	2015–2020	PHEV: 1.5
Yaksic and Tilton [9]	No	~	2100	EV: 1.27

Table 3.1
Annual vehicle sales (millions) in 2050 under the IEA 'Blue Map' and 'Blue EV shifts' scenarios. .
Source: IEA [6]

	HEV	PHEV	BEV	FCV
Blue map	14	62	47	34
Blue EV shifts	6	20	104	0

Implications for the EV market in 2050 based on the IEA scenarios are summarised in Table 3.1.

3.2. Estimating lithium intensity

Current electric vehicle designs commonly use lithium-ion (Li-ion) batteries [53]. As discussed in Section 3.2.2 below, a number of Li-ion and Li-metal chemistries are currently being developed and it is likely that lithium batteries will continue to dominate the EV market for the foreseeable future. The lithium intensity, i.e. the weight of lithium per vehicle, must be estimated before any estimates of future EV lithium demand can be made based on the EV uptake scenarios previously discussed.

Deriving lithium intensity for Li-ion batteries ideally requires knowledge of:

- the nominal voltage of the battery (volts, V);
- the specific capacity of the battery chemistry (Ampère-hours per gram, Ah/g); and
- the concentration of lithium in the active materials of the battery when this is assembled (weight percent, wt%).

While large batteries are required for BEV and PHEV designs, smaller batteries of the order of 1 to 1.5 kW h are generally sufficient for HEVs and FCVs, where they allow storing energy generated on board via regenerative braking and shaving the peaks and troughs of fuel cell duty cycles. Since the capacity of PHEV and BEV batteries is likely to be 10 to 20 times that of HEV and FCV batteries, and since HEVs and FCVs make up a relatively small proportion of the total vehicle market in 2050 based on the IEA scenarios presented in Table 3.1 above, the total lithium demand from HEVs and FCVs is likely to be negligible for the purposes of our study and is hence excluded from our analysis [10].

The amount of lithium contained in an EV battery is a function of the size and particular chemistry of the battery, its construction and its rated performance. It is impossible to define with certainty the amount of lithium that each individual EV battery model will require. Nevertheless, we discuss each of the main factors influencing the amount of lithium required in an individual EV battery in turn. On this basis we identify a range of values for lithium demand per vehicle which is then combined with the global EV demand projections discussed above in order to estimate future global demand for lithium for the EV market.

The calculation of the global lithium demand for EVs in year y ($D_{\mathrm{Li,y}}$) can be summarised by the following equation:

$$D_{\mathrm{Li},\,y} = (M \times S \times I)_{\mathrm{BEV}} + (M \times S \times I)_{\mathrm{PHEV}} \tag{3.1}$$

where M is the market size (annual vehicle sales) of BEVs/PHEVs in year y, S is the average size (kW h) of a BEV/PHEV battery in year y, and I is the average intensity (amount of lithium per unit energy capacity (kW h) of a BEV/PHEV battery in year y).

A similar approach has been taken implicitly or explicitly in a number of relevant studies reviewed here (see Table 3.4). In the following sub-sections we discuss average battery sizes and average amounts of Li per unit energy stored in turn. The analysis presented below allows us to arrive at a plausible lithium demand range.

3.2.1. Average battery sizes for BEVs and PHEVs

The rated energy of the battery, expressed in kW h, is one of the main parameters determining the all-electric range (AER) of a BEV or PHEV. The rated energy is declared by the manufacturer and its relationship with the lithium content is not transparent. The energy stored in an EV battery (and hence its lithium content) is usually significantly higher than its rated energy would suggest, for reasons discussed in Section 3.2.2. Here we will focus on the average rated energy of EV batteries, which we will refer to as battery size.

There is no standard battery size for BEVs and PHEVs. Automotive Original Equipment Manufacturers (OEMs) may decide to manufacture different types of BEV or PHEV with different AER capabilities and therefore different battery sizes. Trade-offs exist between AER on the one hand and cost, weight and volume of the battery on the other. This constrains the extent to which battery size can vary across different models of BEVs and PHEVs. In particular for PHEVs, research carried out at Imperial College London reinforces this point by demonstrating that from a pure techno-economic perspective the optimum battery size is within a relatively narrow range around 15 kW h, independently of the size of the car [16].

BEV models currently being commercialised generally use Li-ion batteries capable of storing ~16–35 kW h, depending on the size of the car, delivering maximum ranges of ~130–180 km (Table 3.2). Disruptive battery technology innovation can have an impact on EV battery size, as we discuss in Section 3.2.4.

Today's PHEVs also use Li-ion batteries; however, compared to BEVs, their size varies significantly across vehicle models (see Table 3.3). This is due to the fact that different powertrain architectures are possible, which are suited to using different modes of operation and to achieving different all-electric ranges. In particular, the Toyota Prius plug-in has been designed to have limited all-electric operation capabilities and hence has a small battery pack (in the order of 4.3 kW h). On the other hand, range-extended electric vehicles such as the Chevrolet Volt are capable of

Table 3.2
Key technical specifications of BEV models on the market in the UK as of July 2013. , OEM websites, Car Magazine website.
Source: DECC [17]

BEV model	Battery energy (kW h)	Range (km)	Max speed (km/h)
Smart fortwo electric drive	16.5	140	100
Citroen C-Zero	16	130–160	130
PuegeotiOn	16	150	130
Mitsubishi i-MiEV 2012	16	150	130
Nissan Leaf	24	160	140
Renault Fluence Z.E.	22	160	135
Renault Zoe	22	160	135
Mia electric	12	120	100

Table 3.3
Key technical specifications of PHEV models on the market in the UK as of July 2013. , OEM websites, Green Car Congress website.
Sources: DECC [17]

Vehicle model	Battery energy (kW h)	EV range (km)	Max EV speed (km/h)
Toyota Prius plug-in hybrid	4.3	20	100
Chevrolet Volt	16	60	190
Vauxhall Ampera	16	60	N/A
Volvo V60	11.2	50	120

delivering high performance while operating in EV mode and hence have a significantly larger battery pack (16 kW h).

3.2.2. Lithium content per unit of energy stored in batteries for BEVs and PHEVs

The amount of lithium required per kW h of battery is an important determinant of total demand for lithium in electric vehicles. However, its estimation is far from straightforward, contributing to the wide range of figures reported in the literature. There are different methods used to derive these estimates, each with its own limitations. Here we discuss the main factors affecting these estimates, following an approach similar to a number of existing studies [12,18–21]. We also discuss the main differences between our approach and others.

Estimating material intensity in batteries ideally requires knowledge of the voltage that the battery is capable of delivering while in operation, its specific capacity[6] and the chemical composition of its active materials. However, this information is only readily available to the battery manufacturers. One method of estimating material intensity (labelled method 'A' in Table 3.4) is to quote industry data where available. This is done in several of the studies cited in Table 3.4. Alternatively, it is possible to measure voltage and specific capacity of a battery, then disassemble it and analyse its composition in a laboratory. This process (labelled 'B'), sometimes referred to as "reverse engineering", is often not practical as it is expensive and results obtained for one particular type of cell would not apply to others. The two remaining options are: to use published data for battery voltage and specific capacity and then make assumptions on composition (labelled 'C'); or to estimate the amount of Li required by starting from the theoretical value required under ideal conditions and then adding to it so as to account for real operating conditions (labelled 'D'). In the following discussion we examine the latter approach. As it will become apparent from the discussion, we will not be able to arrive at specific Li intensity values for EV batteries by simply following this approach. However, it will enable us to assess the validity of some of the figures found in the literature and hence obtain a narrower and more plausible range of Li intensity values that can be used in the remainder of our analysis.

There are three key factors which vary and must be accounted for in a theoretical assessment of lithium intensity in EV batteries:

1. Variation in lithium intensity between different battery chemistries; a number of lithium chemistries are possible and this must be explicitly accounted for.
2. Impact of energy losses on lithium intensity; lithium batteries, like any other battery, when operating only deliver as electricity part of the chemical energy stored, while the rest is lost as heat due to internal resistance mechanisms called "overpotentials".
3. Impact of over-specification on lithium intensity; the actual capacity of a lithium battery is often much higher than the rated capacity, in order to guarantee durability.

These are dealt with in turn below.

3.2.2.1. Variation in lithium intensity between different battery chemistries. First, the amount of lithium used per kW h depends on the stoichiometry of the electrochemical reaction for the battery considered.[7] and on its corresponding electromotive force (E_0).[8] Based on Faraday's laws, the theoretical Li demand per kW h can be calculated as:

$$I = \frac{m \times 10^3}{E_0 a c} \tag{3.2}$$

where I is the lithium intensity in g/kW h, m is the molar mass of lithium in g/mol, E_0 is the electromotive force in volts, a is the fraction of lithium available and c is the charge of 1 mol of lithium ions in Ah/mol.

Using the appropriate values we get:

$$I = \frac{6,941}{E_0 a \times (96,485/3600)} \tag{3.3}$$

For example, the conventional Li-ion chemistry (originally commercialised by Sony) is based on the following redox process:

$$6C + LiCoO_2 \leftrightarrow Li_{0.5}C_6 + Li_{0.5}CoO_2 \qquad E_0 \approx 4\ V \tag{3.4}$$

where the cathode material $LiCoO_2$ can only exchange roughly half of its lithium content, hence the fraction of lithium available (a) would be 50%. Entering these values in the formula the theoretical amount of Li needed per kW h of a conventional Li-ion battery would be 129.5 g.[9]

Another relevant Li-ion chemistry uses lithium iron phosphate ($LiFePO_4$) cathodes and lithium titanium oxide ($Li_4Ti_5O_{12}$) anodes; this chemistry is inherently safer than the one previously discussed and hence potentially more suited to EVs, particularly PHEVs. The electromotive force (E_0).[10] of this system is ≈ 2 V. If we assume that 100% of the Li contained in $LiFePO_4$ and 75% of the Li contained in $Li_4Ti_5O_{12}$ can be made available.[11] the theoretical amount of Li needed per kW h will be 172.6 g. The two examples

[6] The total current that the battery can deliver when discharged per unit weight of the battery.

[7] The degree to which specific anode and cathode materials can make available the Li that they contain is a factor which should be accounted for, as this varies significantly across Li-ion battery electrode materials and depends on their ability to release the Li contained without their microscopic structure being affected.

[8] For more detail on these and other electrochemistry concepts, refer to relevant textbooks [22], [23].

[9] Or 689g of lithium carbonate using a conversion factor of 5.33.

[10] Electromotive force is the voltage measured at the battery electrodes at open circuit, i.e. when no current is being drawn.

[11] These are commonly made assumptions based on the structure of the materials.

Table 3.4
Estimates of lithium carbonate (Li_2CO_3) usage per kW h found in the literature.

Source	Vehicle application	Material intensity (kg Li/ kW h)	*Methodology* [a]
Chemetall GmbH [28]	BEV (25 kW h)	0.165	A
	PHEV (16 kW h)	0.176	
	HEV (1 kW h)	0.375	
Meridian International Research [7]		0.300	A
Meridian International Research [20]		0.563	D
Kushnir and Sanden [18]	Average for four chemistries	0.160	D
Rade and Andersson [19]	Li-ion (Mn)	0.140	D
	Li-ion (Ni)		
	Li-ion (Co)		
Argonne National Laboratory [26]	HEV4 (1.2 kW h)	0.308	C
	PHEV20 (6 kW h)	0.244	
	PHEV40 (12 kW h)	0.246	
	EV100 (30 kW h)	0.246	
Gruber et al. [17]	Li-ion (Co, Mn, Ni)	0.114	D
Evans [29]		0.113	A
Evans cited by Reuters [30]	Chevrolet Volt (16 kW h)	0.158	A
Engel [25]		0.050	A
Fraunhofer ISI [12]	$LiCoO_2$	0.180	D
	$LiFePO_4$	0.120	
Dundee Capital Markets [11]		0.080	A
National Renewable Energy Laboratory [27]	HEV (1.7 kW h)	0.100	Internal modelling study (C or D)
	PHEV12 (5.6 kW h)	0.108	
	PHEV35 (17.5 kW h)	0.110	
	BEV75 (29.5 kW h)	0.112	
	BEV150 (67 kW h)	0.112	

provided clearly illustrate that Li intensity is not the same for different chemistries.

Calculating g(Li)/kW h in this way provides a theoretical minimum and not the actual Li intensity of real EV batteries. However, starting from the theoretical value is useful, not least because it shows that lithium intensity changes from one battery chemistry to another simply as a result of the different electrochemical processes involved. Actual lithium intensity will be higher than the theoretical value for the two main reasons discussed below.

3.2.2.2. Impact of energy losses on lithium intensity. The voltage of a lithium ion battery when operating is significantly lower than its electromotive force E_0, the difference being a result of resistance within the battery. When the cell is operating, its actual voltage, ΔV (the difference in potential between the electrodes), can be expressed as:

$$\Delta V = E_0 - (iR_I) \tag{3.5}$$

where i is the current being drawn from the cell and R_I is the internal resistance of the cell. R_I is the sum of the ohmic resistance of the electrolyte and electrodes as well as the resistance due to the kinetics of charge transfer at the interface between electrodes and electrolyte. In summary the difference between E_0 and ΔV, usually referred to as overpotential, is a function of both how the cell is operated (i.e. how fast the cell is discharged and the temperature at which it is operated) and how it is constructed (i.e. chemical composition of the electrodes, their density, thickness and size of the particles of active material; the concentration of the lithium salt used as electrolyte and the chemical composition of the solvents used). Hence if we substitute E_0 with ΔV in Eq. (3.2), Li demand per kW h will be higher than the theoretical value because ΔV is always smaller than E_0. The difference between E_0 and ΔV is too complicated to be estimated theoretically from first principles for any battery chemistry. Its experimental measurement on the other hand is straightforward, though the values obtained for a specific battery model cannot be generalised, not even to batteries using the same chemistry.

3.2.2.3. Impact of over-specification on lithium intensity. Manufacturers often 'over-specify'[12] batteries, typically to compensate for degradation through use and hence improve the rated cycle life, which is typically calculated as the number of charge–discharge cycles achievable before energy capacity falls below 80% of the rated value. In many cases the over-specification of the battery is quite substantial, and the depth of charge–discharge cycles is significantly constrained[13]. The extent to which the battery is over-specified can vary greatly across manufacturers, chemistry and intended use of the battery. As a consequence the actual amount of Li present in the battery can increase by as much as a factor of two.[14]

Given these problems of energy losses and over-specification it is hard to calculate lithium intensity directly we examine stated lithium intensities of Li-ion batteries available in the literature (see Table 3.4). The range varies widely, between 50 g/kW h and 562 g/kW h, and not all of the estimates in the list have the same merit. First, not all methodologies labelled 'A' are actual industry sources, as many are quoted in the media or in corporate presentations without reference to either public or proprietary industry data. We discount a number of these estimates on this basis, as well as for values lower than theoretical limits [11,26]. Methodology 'C' is valid, although the study using it [27] does not disclose justifications or references for the assumptions used. Within the studies employing methodology 'D', Tahil [21] and Angerer et al. [12] appear to overstate lithium intensity, while Gruber et al. [18] assume lower values [10]. Finally, a number of studies do not disclose the full details of their assumptions or methods [19,28]. These observations make it difficult to judge the value of many

[12] i.e. they manufacture batteries that can perform significantly better than the rated values.

[13] Fully charging and discharging the battery mechanically stresses the electrode materials and generally results in faster degradation. For more details see for example [24]

[14] See for example Eberle and von Helmolt [25], where the authors report that despite the 16 kW h nominal energy of the battery of the new Chevrolet Volt PHEV, it is operated at 50% maximum depth of charge-discharge and hence the actual usable energy is only 8 kW h.

estimates in Table 3.4. For this reason in Section 5 we use a range (190 g/kW h to 380 g/kW h) of illustrative lithium intensities. This range is based on lithium intensity estimates found in the literature [10], excludes estimates which appear close to theoretical minimum lithium intensities [11,26], and excludes apparent overestimates [10,21].

Based on the evidence presented above it is fair to conclude that the only practical way of knowing the demand of lithium used per kW h for a given model of battery is to rely on industry data, where they are available. Failing this, estimates such as those made by Tahil [21] and Gaines and Nelson [27] are useful albeit affected by significant uncertainty.

3.2.3. *Potential for lithium weight shedding*

The focus of research and development in lithium batteries is currently aimed at increasing safety, lowering cost, increasing energy density and improving cycle life, with a long-term view towards lower environmental impact [29,30]. Raw lithium contributes only 1–2% of final battery cost [19]. Accordingly, little discussion about reductions in lithium content can be found in the literature. Rade and Andersson [20] provide one of the few estimates of future lithium intensity of Li-ion batteries based on the improvement of active material utilisation (the amount of lithium content in the anode and cathode that can be made available in the reaction) from a current 50% to 60–80% depending on chemistry, leading to intensity reductions of 21–34%. It is worth noting that it is unclear whether these developments will be realised.

Two alternative lithium-based chemistries currently being developed are lithium–air [29] and lithium–sulphur [31]. Both of these technologies have higher energy density and thus ability to improve the driving range of electric vehicles compared to Li-ion batteries currently on the market. Improvements associated with these technologies may increase both the market share of lithium batteries as well as the average size (kW h) of EV batteries, resulting in an overall increase in annual demand for lithium as per Eq. (3.3). In order to reduce lithium demand in EV applications it may therefore be necessary to substitute lithium completely in EV batteries.

3.2.4. *Potential for substitution*

Early BEVs such as General Motors' EV1 used lead acid batteries and more recently the Think City used Sodium/Nickel Chloride (also known as ZEBRA) batteries. However, lithium batteries have significant advantages over these two battery types and it is unlikely that they will be used in future BEVs and PHEVs. Since lithium is the lightest metal and has an extremely negative electrode potential, lithium batteries have much higher energy density than lead-acid batteries, allowing EVs to achieve acceptable ranges without imposing a high weight penalty. Unlike ZEBRA batteries which use molten Sodium at 300–350 °C, lithium batteries operate at room temperature and because they don't need preheating they are always available for use, which is a very desirable characteristic for vehicles with no fixed usage patterns such as passenger cars. These favourable characteristics, together with the high power density and long cycle life, explain why lithium batteries are the current technology of choice for BEVs and PHEVs.

Other non-lithium chemistries are being researched at present which may compete with lithium batteries. However, alternatives to lithium are limited, because prospective systems need to have high energy density and achieving this requires light metals such as sodium, magnesium and aluminium. Battery systems currently under investigation include magnesium/sulphur and aluminium/graphite fluoride. However, the practical viability of these systems has not been demonstrated and their future use in electric vehicles depends on significant technological improvement [29]. Metal air chemistries such as sodium air and zinc air are also possible alternatives to lithium air. Sodium air batteries in particular have the potential to mitigate some of the problems of Li–air technology but technological improvement is needed before this technology becomes practical [32].

To summarise, alternatives exist though in the short to medium term lithium-based chemistries seem favoured, while in the long term other options may become competitive, giving rise to potential substitution. However, alternative technologies are currently far from mature and technological improvement is still needed.

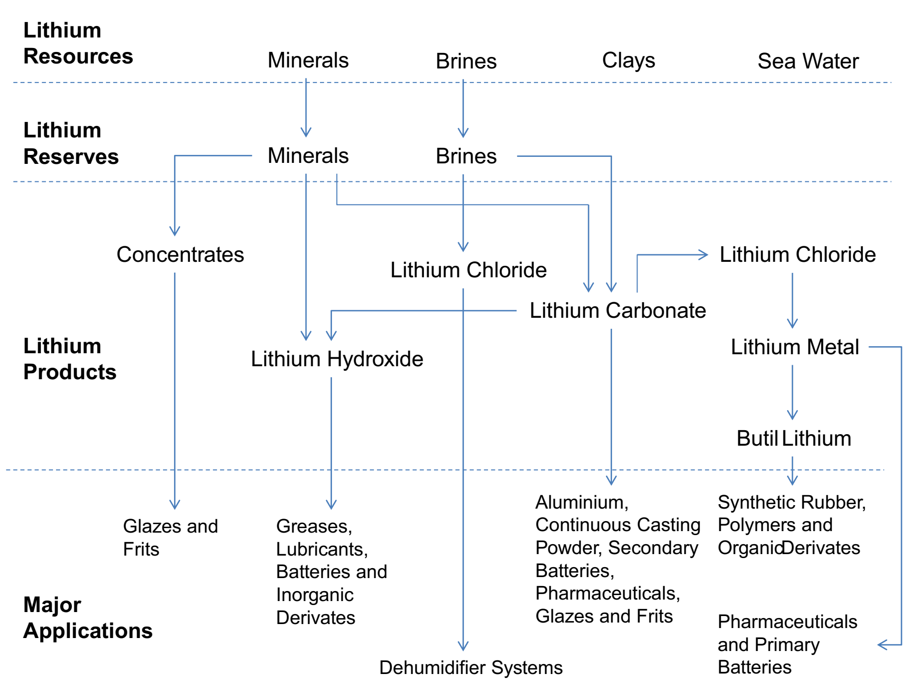

Fig. 4.1. Sources and chemical forms of lithium and their major applications. *Source*: Yaksic and Tilton [9].

4. Lithium supply

The future availability of lithium is contingent upon the rate at which lithium can be produced and brought to market over the coming decades. To understand future lithium supply issues we explore: lithium's geological characteristics and the routes to its extraction; existing reserve estimates and current production rate; the extent to which lithium can be recycled; and forecasts of future lithium production.

4.1. Geological characteristics of lithium

Due to its reactivity, lithium metal never occurs freely in nature, and is instead found in four main deposit types: minerals, brines, sedimentary rocks and seawater. Minerals and brines constitute the world's source of lithium today. Lithium-containing minerals are typically coarse-grained intrusive igneous rocks known as pegmatites, such as spodumene, petalite, lepidolite, amblygonite and eucryptite [18]. Brine deposits are currently the largest and cheapest sources of lithium [9] and are mostly found in dry lakes such as the Salar de Atacama in Chile, as well as geothermal deposits and saline aquifers. The third source of lithium is in sedimentary rocks, notably clays such as hectorite, and lacustrine evaporates such as the newly discovered jadarite [18,33]. These sedimentary deposits are not commercially recovered. Finally, seawater contains diffuse but very large quantities of lithium. According to Yaksic and Tilton [9], 44.8 billion tonnes of lithium are recoverable from the world's oceans. The economic viability of extracting lithium from sea water is uncertain.

Lithium is not produced in its elemental (metallic) form but as lithium carbonate, lithium hydroxide, lithium chloride and other forms shown in Fig. 4.1. Different forms of lithium are used in different applications. Lithium carbonate is the form typically used to manufacture Li-ion batteries.

Of the major producers of lithium by content (see Fig. 4.2) Chile and Argentina both produce lithium carbonate from brine, while Australia produces lithium in minerals recovered from spodumene deposits. China's production is split between mineral production and lithium carbonate production from brine, with lithium minerals containing 35% of China's reserves while brines contained 65%.

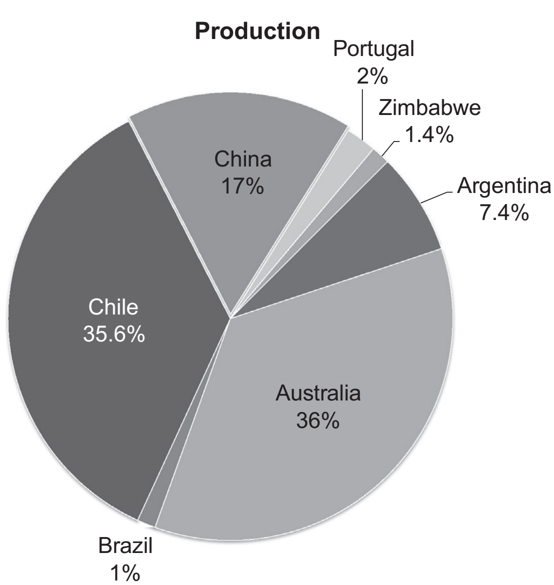

Fig. 4.2. Distribution of lithium production and reserves in 2011. *Source*: USGS [37], *Note:* Data are in metric tons of gross product of lithium minerals and brine. USGS do not disclose US production data.

4.2. Production and reserves

Known reserves[15] of lithium exist and are produced in a number of countries, the relative distribution of which is presented in Fig. 4.2. The largest share of both production, and reported reserves occur in Chile, which recovers lithium from brine pools located in salt flats throughout the Andes mountain range. The geographical distribution of both reserves and production indicates that lithium supply is unlikely to suffer from the geopolitical supply constraints witnessed for materials with less well geographically distributed resources such as rare earth metals or indium [10,34–36].

Fig. 4.3 presents lithium production data published by the USGS. Since 1967, lithium production was reported as 'ore and ore concentrates' from mines and lithium carbonate from brine deposits. Calculating the lithium metal weight in lithium carbonate is relatively simple (see footnote 5). However, calculating the metal content of ore and ore concentrate is problematic given that the composition of these ores and concentrates is unknown.

Despite inconsistencies in data, Fig. 4.3 appears to presents a resource which is being exploited through an exponential phase of production.

Fig. 4.4 presents several different lithium reserve and resource estimates. This figure presents a number of different classifications of resources (see notes). It is important to note that, where reserve classifications differ, estimates are not directly comparable. This issue is compounded by the fact that explicit descriptions of reserve classifications are not always provided by authors.

The USGS present figures for reserves and reserve base15, though reserve base reporting was discontinued in 2010. Roskill (cited in Engel-Bader [38]) also present reserve data for 2009. In 2004, disaggregate reserve figures are presented by Garrett [39]. Reserve and reserve base estimates from Tahil [7,8] are presented in years 2005 and 2007. In year 2008 reserve and 'in situ' data from Evans [40] are presented. Finally Yaksic and Tilton [9] provide estimates of recoverable resources and in situ resources in 2009, which are also included. This data presents a considerable range of estimates, with the largest estimate in 2009 over 700% greater than the smallest. This can in part be explained by the differing natures of reserve classifications, but it also reflects the range of estimates regarding the future prospects for lithium production. It is also worth mentioning that the USGS refer to additional "resources" for several countries, including Bolivia, which as yet has no recorded production or reserves, but the USGS [37] estimate it to have 9 million tonnes of resources. What prevents any of these resources from being reported as reserves by the USGS is unclear. The USGS [37] estimate world resources at 34 million tonnes, over twice their reserve estimate in the 2012 issue of the but still less than half the Yaksic and Tilton [9] estimate.

Given the nature of increasing production (Fig. 4.3), and the relative increases in reserve estimates over time (Fig. 4.4), lithium appears to be relatively immature in terms of its exploration and production, with production increasing rapidly every year, and

[15] Reserves: "That part of the reserve base which could be economically extracted or produced at the time of determination…… Reserves include only recoverable materials…."Reserve Base: "That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the …. resource from which reserves are estimated… The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).Resources: A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible."

reserve estimates indicating that new resources are still being discovered.

a. Reserves
b. Recoverable resources
c. Broad based reserves
d. Reserve base
e. in situ resources
f. Ultimate global reserve base
g. Identified Resources

4.3. Recycling

Historically, only small quantities of lithium have been recycled [41]. The United Nations Environment Programme estimates lithium end-of-life recycling rates at less than 1% [42]. However, there has been an increase in use recently due to battery applications with accompanying increases in regulation of the disposal of waste batteries. In Europe, Member States must collect 25% of end-of-life batteries by 2012 and 45% by 2016 [43]. This legislation does not necessarily imply nor mandate the recycling of lithium metal. In fact, some Li-ion battery recycling facilities recover cobalt and nickel hydroxides but not lithium [44].

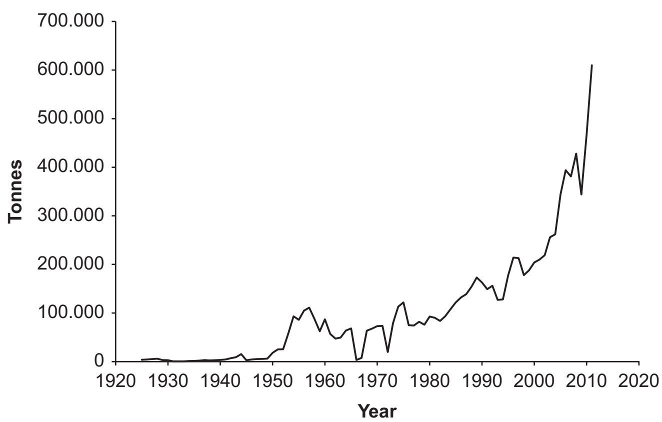

Fig. 4.3. World annual production of lithium ore and ore concentrate from minerals, and lithium carbonate from brines, 1925–2011, , *Notes:* No US data after 1954. No data for Rhodesia (Zimbabwe) and other African countries between 1966 and 1967. 1 kg of lithium metal = ~5.33 kg lithium carbonate. No accurate conversion factor available for lithium metal content of reported ore and ore concentrate. *Source:* USGS

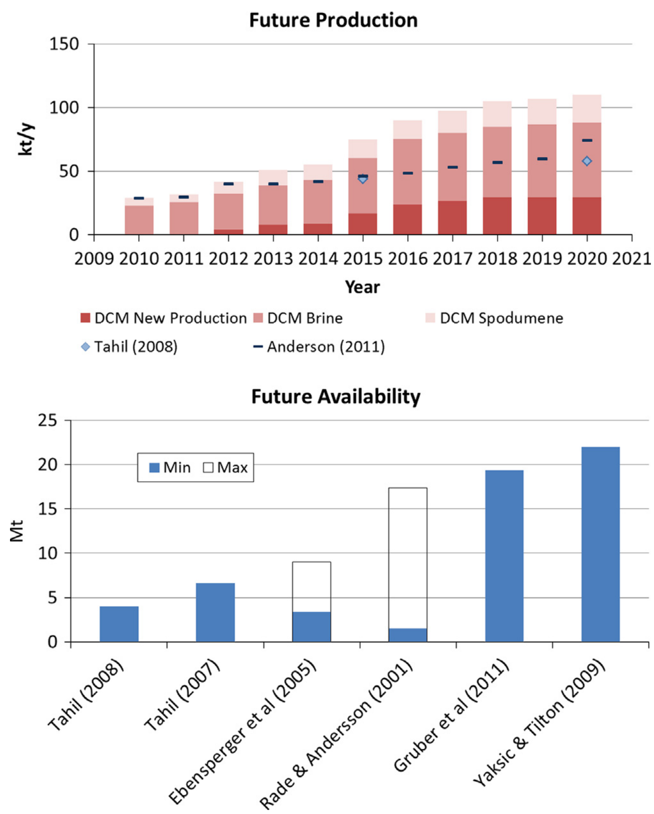

Fig. 4.5. Available estimates of future annual production and future cumulative availability of lithium. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

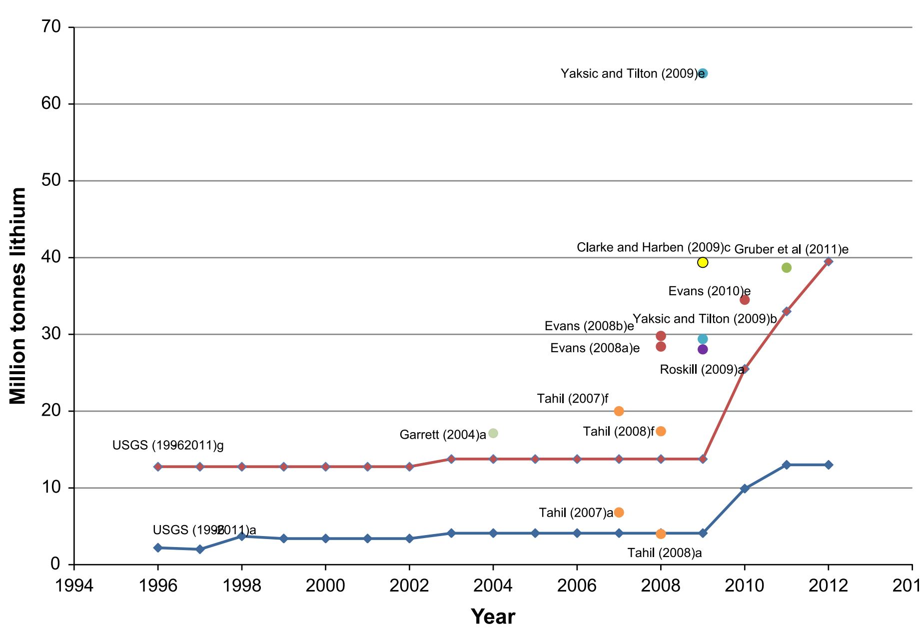

Fig. 4.4. USGS annual reported reserves and other available estimates from existing literature, *Notes:* Several different reserve and resource definitions are represented in the estimates in this figure. Where available the definitions are provided in Speirs et al. [10].

Nevertheless, the potential for recycling of lithium from end-of-life batteries is estimated to be significant. Gaines and Nelson [27] estimate that over 40,000 t of contained lithium could be recycled in the US by 2050, assuming 100% recycling rates and a 10-yr battery life. Gruber et al. [18] model lithium recycling and estimate that this could satisfy between 50 and 63% of cumulative demand over the 2010–2100 period, assuming recycling rates of 90–100%. Buchert et al. [44], however, note that while the large growth in battery production implies a significant recycling potential, there is currently a lack of economic incentive to recycle lithium given its relatively low price.[16]

A primary issue in recycling lithium from end-of-life batteries is the sorting of collected waste batteries. Not all collected batteries will be Li-ion batteries, e.g. in the automotive sector many will still be NiMH, and not all Li-ion batteries have the same chemistry. In order to develop an efficient recycling process, it is necessary to know the composition of the batteries to be treated [46]. A number of automatic sorting systems have now been developed for waste batteries, using magnetic or electrodynamic sensors, photo recognition of the label and x-ray imaging, all resulting in varying levels of purity in the separated fractions [47].

The recovery of lithium from spent batteries remains a niche market [44], and the battery industry does not currently produce batteries using recycled material [48]. It therefore appears difficult for recycled lithium to contribute half of future supply, as suggested by Gruber et al. [18], and more targeted legislation or a clear economic incentive will be required.

4.4. Estimates of future supply

Both production and reserve estimates are likely to change over time and several authors have tried to account for these changes within estimates of future production or availability. Fig. 4.5 presents estimates of both future production and future availability. Future production estimates are based on analysis of future lithium projects while future availability is estimated by estimating total recoverable resources. These estimates are in the order of 60 to 110 thousand tonnes per year of lithium metal production in 2020 and ~2 to ~20 million tonnes of lithium metal available over the century to 2100 or over all time.

The future production chart in Fig. 4.5 contains estimates from three sources. A fourth source [9] estimates future production of lithium metal in 2100 at 330 thousand tonnes per year. This estimate has been omitted given its long time horizon.

A report by Dundee Capital Markets [11] presents a projection for lithium supply to 2020. This data is subdivided into lithium production from brines, lithium production from spodumene minerals, and lithium from new production capacity forecast to come onstream from 2012. These data are represented by the red bars in Fig. 4.5, and forecast lithium production of ~110 thousand tonnes per year in 2020. Anderson [49] presents a similar supply forecast to 2020, with slightly more conservative lithium production figures of ~75 thousand tonnes per year in 2020. Finally Tahil [8] presents two spot estimates for future lithium production, estimating 44 thousand tonnes per year in 2015 and 58 t per year in 2020.

Based on the evidence presented in Fig. 4.5 production of lithium in 2020 is estimated at between 58 and 110 t per year.

To put this range in context estimates of available lithium resources range from 4 to 22 million tonnes, with the USGS estimating 13 million tonnes of lithium reserves. However, significantly more lithium may be available if lithium prices increase. Yaksic and Tilton [9] estimate that, at a cost of between $1.40 and $2 per lb of lithium carbonate, 22 million tonnes of lithium is available. However, they also estimate that at a cost of between $7 and $10 per lb of lithium carbonate, lithium can be extracted from seawater, more than doubling their estimate of available lithium.

Given the conservative nature of common reserve estimates, and the resulting behaviour that these estimates typically increase over time, it is practical to assume the latest reserve estimate as a lower bound for estimates of future lithium availability. Given the current USGS lithium reserve estimate of 13 Mt, and the conservative nature of these types of estimate it is reasonable to discount those estimates in Fig. 4.5 that are lower than 13 Mt. This leaves the upper estimate provided by Rade and Andersson [20], the Gruber et al. [18] estimate, and the Yaksic and Tilton [9] estimate. This gives a range of 13 Mt to 22 Mt.[17] for future availability of lithium.

5. The balance of future lithium supply and demand

In Table 5.1, illustrative ranges of demand for lithium from BEV and PHEV batteries are presented for 2030 and 2050. These are presented as 'low' and 'high' material intensity cases in each of the estimate years. Due to the complexity in estimating the lithium content of batteries, we use indicative figures for lithium intensity (g Li/kW h) from the discussion in Section 3. The 'low material intensity' case uses an average battery size of 4.3 kW h in PHEVs, and 16 kW h in BEVs, based on the lowest value found in the literature [9]. The 'high material intensity' case uses indicative figures from today's BEVs and PHEVs (see Table 3.2 and Table 3.3). The annual sales figure is that projected in the IEA's BLUE Map scenario detailed in Table 3.1. No account of other uses of lithium is included in the demand estimates, and these are purely based on demand for EVs.

In the illustrative estimates above lithium demand from electric and hybrid vehicles increases significantly between 2030 and 2050. This is mainly due to the large growth in annual vehicle sales between the two estimates, and the changing ratio between PHEV and BEV sales, which have different battery sizes (kW h). The scale of future demand is also very large, with almost one million tonnes of lithium demand annually in the 2050 market high intensity case.

On the left of Fig. 5.1 we present historical lithium metal production, using data from Fig. 4.3 showing the approximately geometric growth in supply to date. The future lithium supply estimates, presented in Fig. 5.1 are limited, both in number and in timescale. The high supply estimate, however, represents a two to three fold increase in production by 2020, maintaining the historical compound rate of growth, if not exceeding it. The quantitative impacts of recycling on supply are not included given the ongoing concerns regarding lack of economic incentive and the low recycling rate experienced currently. However, if lithium recycling increased in the future this would have a positive impact on future lithium availability relative to the estimates presented in Fig. 5.1.

The range of demand presented in Fig. 5.1 is large, driven by several factors. First, there is significant uncertainty regarding the future average battery size and lithium intensity in batteries. There is a paucity of literature discussing the likely development of these factors over time, and the current vehicle fleet data and reports provide a very wide range of battery sizes and material intensities. However, the low estimate of future demand is unlikely to be reduced without reducing assumptions on car sales in 2030 or 2050. The main priority currently pursued by EV manufactures is increasing vehicle range rather than decreasing material intensity.

[16] Lithium price is often reported as the price of lithium carbonate. In 2011, the average price of lithium carbonate was approximately $4.3/kg [45].

[17] Based on the assumption that lithium carbonate remains around $2/lb.

Table 5.1
Illustrative ranges of lithium demand for battery electric and plug-in hybrid vehicles in 2030 and 2050 markets.

Variable	Low material intensity	High material intensity
Battery size (kW h)—PHEV[a]	4.3	16
Battery size (kW h)—BEV[a]	16	35
Intensity (g Li/kW h)[b]	190	380
2030 BLUE Map market		
Annual sales (million units/yr)—PHEV	25	25
Annual sales (million units/yr)—BEV	9	9
Market share of Li-ion batteries	100%	100%
Range of demand (kilotonnes Li/yr)	**47.2**	**268**
2050 BLUE Map market		
Annual sales (million units/yr)—PHEV	62	62
Annual sales (million units/yr)—BEV	47	47
Market share of Li-ion batteries	100%	100%
Range of demand (kilotonnes Li/yr)	**184**	**989**

[a] Battery size used in the lowest material intensity case based on Table 3.2 and 3.3; the values in the highest material intensity are illustrative.
[b] Based on an illustrative range for lithium carbonate intensity of 1–2 kg/kW h.

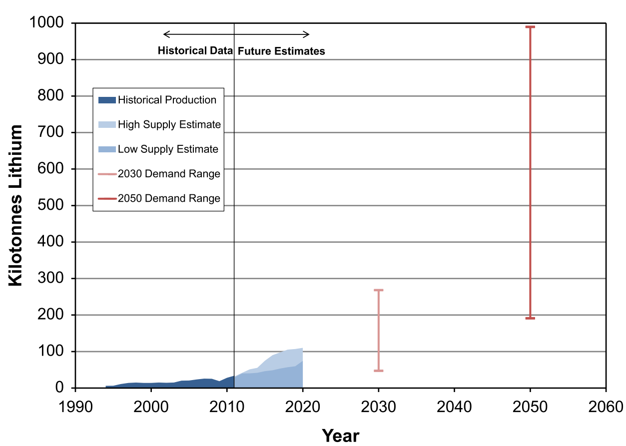

Fig. 5.1. Lithium: comparison of historical production, forecast supply, and forecast demand.

It is reasonable therefore to assume that battery size and material intensity are more likely to increase in the coming years. The difference between estimates in 2030 and 2050 is entirely driven by the assumed growth in vehicle sales.

The estimated range of future demand is many times greater than current supply. While this is challenging there is no evidence that future production cannot increase at a sufficient pace. Though long term exponential growth in lithium production would be unsustainable, if growth could be sustained over the next two decades, meeting future demand may be possible. Supporting this optimism are the significant resource estimates for lithium seen in Fig. 5.1, though these estimates make no assessment of how easy these resources are to access, and over what timescales they can be produced.

6. Conclusions

There is growing concern over the availability of lithium for the future manufacture of electric vehicles. However, the paucity and poor quality of literature assessing availability of materials for electric vehicles is a key issue. Lithium availability for EV batteries has been assessed in only a few studies [9,18,50]. Lithium has also been examined at a broader level in conjunction with other so-called 'critical metals' in a number of studies [1,2,12,51,52], and often the evidence base for concerns over availability consists primarily of this less detailed literature.

This paper has examined the key variables needed to make an assessment of future lithium availability. On the demand side, these variables include future market size of electric vehicles, their average battery capacity, and their material intensity. We have gathered and presented the literature base for these three factors and used them to provide a range of demand for lithium for electric vehicles in 2050. In several cases, however, illustrative assumptions have been made owing to a lack of evidence or published estimates. This paper highlights a wide range of lithium demand assumptions in the literature, especially due to the large uncertainty in material intensity assumptions for EV batteries, which range from 50 to 563 g Li/kW h.[18] The range of uncertainties in various factors leads to a wide range of estimated demand for 2050. A key objective for future assessment of material availability is reducing this uncertainty range through improved information availability and a better understanding of the key variables of technological demand. This paper also touches on possibilities for reductions in material intensity via new lithium battery chemistries or substitution. While it is possible that new lithium battery chemistries will contribute some reductions to material intensity, chemistries that could substitute for lithium batteries have not yet been demonstrated at a commercial scale and it is difficult to draw conclusions on their full potential.

In addition to the uncertainty surrounding material intensity, there is also no consensus on the future market share of BEVs and PHEVs versus that of HEVs and FCVs, which have smaller batteries and thus contain less lithium. This paper uses the uptake scenarios and market size of the IEA, because their projections are commensurate with a 50% reduction in carbon emissions by 2050. The IEA's scenario for BEV and PHEV estimates significant but plausible uptake of these vehicles. Given this level of uptake demand for lithium in 2050 is likely to be high.

The key supply variables include global reserve and resource estimates, forecast production and recyclability. There is little consensus in the evidence base about the global quantity of lithium reserves and resources. However, estimates seem to increase in recent years, reflecting the increasing demand for lithium which has driven successful exploration for new resources. It is common in the published literature to find that future lithium availability is measured by comparing reserves or resources with anticipated demand. This method gives little information about the rate at which production can be increased. As a result, we have focused on estimates of future production. However, there are few estimates of future production. Lithium production forecasts vary from 75 to 110 kt in 2020 and it is likely that lithium production could increase in coming years to meet increasing demand given the increasing reserve estimates.

Finally, if the market for EVs grows as substantially as suggested by the IEA Blue Map scenario then the implications of anticipated 2050 demand for lithium will be significant, exceeding 2012 production by up to 2600%. Although this is challenging, there is no evidence suggesting a physical barrier to increasing production to at least the midpoint of the 2050 demand range. Identified resources excluding seawater appear substantial, and end-of-use recycling could contribute to future supply if the vehicle market grows as strongly as forecast by the IEA, although it is unclear which lithium price levels will make this recycling viable. Future analysis of material demand for electric vehicles is needed to assess the issue of present and future material intensity,

[18] We constrain this uncertainty to between 190 and 380 g Li/kW h in Table 5.1

in order to reduce uncertainty concerning the quantity of lithium demanded per battery in the future. Analysis of the production potential of lithium is also needed to better assess which parts of identified lithium resources are economic. While there is evidence in the literature that these steps are being taken, a thorough assessment of the long term effects of material availability on the deployment of electric vehicles still requires a much improved understanding of the potential for, and the economic implications of, expansion in both lithium production and recycling.

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